D 851362

NASA Technical Memorandum 87341

Computational Simulation of Progressive Fracture in Fiber Composites

(NASA-TM-87341) COMPUTATIONAL SIMULATION OF PROGRESSIVE FRACTURE IN FIBER COMPOSITES (NASA) 12 p HC A02/MF A01 CSCL 11D
N86-26376
Unclas
G3/24 43288

Christos C. Chamis
Lewis Research Center
Cleveland, Ohio

Prepared for the
International Conference on Computational Mechanics
sponsored by the International Committee on Computational Mechanics
Tokyo, Japan, May 25-28, 1986

NASA

E-3090

COMPUTATIONAL SIMULATION OF PROGRESSIVE FRACTURE IN FIBER COMPOSITES

Christos C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

Computational methods for simulating and predicting progressive fracture in fiber composite structures are presented. These methods are integrated into a computer code of modular form. The modules include composite mechanics, finite element analysis, and fracture criteria. The code is used to computationally simulate progressive fracture in composite laminates with and without defects. The simulation tracks the fracture progression in terms of modes initiating fracture, damage growth, and imminent global (catastrophic) laminate fracture.

INTRODUCTION

Prediction of progressive fracture of composite laminates is fundamental to developing the methodology for quantifying composite structural durability and reliability. NASA Lewis Research Center is conducting fundamental theoretical and experimental research programs to develop formal methods and procedures for determining progressive composite fracture. The theoretical studies include the development of composite mechanics, combined stress failure criteria, criteria for identifying predominant fracture modes and associated fracture surfaces, and the development of integrated computer codes for the computational simulation of progressive fracture in fiber composites. The experimental studies include development of methods for real time ultrasonic C-scan of laminates under load in order to detect fracture initiation, damage growth and fracture progression as these events occur. The experimental studies also include development of methods for post-mortem examination of fracture surfaces in order to identify and catalog unique fracture surface characteristics associated with dominant fracture modes.

The theoretical studies previously mentioned led to the development of computational methods for assessing composite structural behavior (integrity, durability and damage tolerance). A major portion of the computational methods development includes the computational simulation of progressive fracture in composites which is the subject of this paper. This simulation is described in terms of (1) the various composite scales (as defined later) and types of fracture modes that occur in these scales, (2) an integrated computer code to perform the simulation, and (3) application of the code to predict progressive laminate fracture.

DTIC-A... 11-2-95

FUNDAMENTAL CONSIDERATIONS

Progressive fracture in fiber composites is a dynamic (real-time) physical process. This process is an accumulation of multiple events triggered by the various stress states and their attendant failure modes present in fiber composites. The various failure modes take place at different scales (levels) in

A-1

the composite. The different levels include: (1) sub-micro scale (intra or within each constituent and the interphase), (2) micro scale (inter-constituent), (3) macro scale (individual plies and interplies), (4) laminate scale (all plies in a line through the thickness of the laminate), (5) local scale, a small region defined by neighboring points in the laminate plane (for example, nodes connecting a finite element) and, (6) global scale (the structural component).

Because of the several failure modes in each scale, fracture can occur as single events at different times in different locations in the composite structure. Or it can occur simultaneously as multiple events in one or more locations in the composite structures. In view of this, it is convenient to discuss progressive fracture using the following definitions: (1) failure initiation - when the stress field induces a failure in the sub-micro scale, (2) defect or flaw formation - when one or more sub-micro scale failures coalesce to form a micro scale failure, (3) ply failure - when several micro defects coalesce to form defects in the macro scale (transply cracks), (4) delamination - when a defect is formed between adjacent plies, (5) laminate failure - when macro defects (transply cracks) coalesce to form a through-the-thickness laminate defect or crack, (6) progressive fracture - when laminate defects progress in the plane of the laminate to form defects in the local scale, and (7) global fracture - when the composite structure fractures in one or more parts. Events occurring in items (1) to (6) are usually combined and are collectively called laminate or composite damage.

Computational simulation of progressive fracture in composites as a real-time dynamic event has not yet been investigated to the author's knowledge. Also, computational simulation of progressive fracture as an equivalent static process starting from the sub-micro scale has not yet been investigated. The computational simulation presently pursued at Lewis is based on the macro scale and it assumes that progressive fracture is an equivalent static process. In this computational simulation, macro scale defects (transply cracks) are formed when the stress field induces failure in one of the ply failure modes (longitudinal tension or compression, transverse tension or compression and intralaminar shear) and/or induces interply delamination. The corresponding ply and interply strengths are predicted using composite micromechanics. The composite micromechanics account for void and hygrothermal effects on the constituents and, therefore, on the ply and interply strengths. Composite micromechanics integrate, in part, the events occurring at the sub-micro and micro scales.

COMPUTATIONAL SIMULATION USING CODSTRAN

Research activities on progressive composite fracture at Lewis during the last ten years have culminated in the development of the CODSTRAN computer code (ref. 1). CODSTRAN (Composite Durability Structural Analysis) has been specifically developed for the computational simulation of progressive fracture in fiber composites.

CODSTRAN is a modular program (fig. 1) that does quantitative calculations to predict defect growth and progressive fracture in composite structural components. Capabilities of CODSTRAN include determining the durability of composites with and without defects, determining structural responses due to mechanical and thermal loads, accurate prediction of stress states near defects (stress concentrations), and prediction of ply and laminate level

failure and fracture. The modules comprising CODSTRAN are: (1) the executive module, containing communication links to all other modules; (2) the I/O module; (3) the Analysis module; (4) the Composite Mechanics Module; and (5) the Fracture Mechanics module.

The Analysis module is NASTRAN (ref. 2) and is used to calculate both near-field and far-field stresses in a finite element model of the structural component or specimen. The Composite Mechanics module (MFCA) (ref. 3) generates laminate properties from constituent properties (composite micromechanics) and uses intraply failure and interlaminar delamination criteria to check ply and interply failure, respectively. The Fracture Mechanics module is able to account for both ply level fracture and laminate fracture. The modified distortion energy principle and/or a general quadratic surface fit are used to indicate combined ply level fracture (ref. 4). Laminate level failure is based on concepts described in references 5 and 6. It is assumed to occur when all the plies in the laminate have failed.

To computationally simulate progressive fracture, CODSTRAN uses an iterative procedure whereby a load is applied to the finite element mesh of the structure being modeled. The response of the structure to the load can be no damage, damage, or destruction of an element(s) (local fracture). Based upon this response, the load increment is updated as follows: (1) if no damage is predicted, the load is updated by some predetermined load increment; (2) if elements are damaged or destroyed (defect growth or local fracture), the same load is re-applied with reduced material properties assigned to the damaged elements. Destroyed elements are purged from the finite element mesh, effectively defining progressive fracture. This load is maintained until equilibrium in the structure is achieved. Equilibrium is defined as the point where the structure, with its updated geometry and modified material properties, can sustain the applied load without the occurrence of further damage. This iterative procedure is continued through load increments until global fracture of the structure occurs. This iterative procedure is depicted schematically in figure 2.

PROGRESSIVE FRACTURE - TYPICAL RESULTS

CODSTRAN has been used to computationally simulate progressive fracture in a composite laminate with a center notch depicted schematically in figure 3 (ref. 1). These laminates were made from Thornel 300 graphite fiber in an epoxy matrix (T300/E). The laminate configuration is $[0/+30/0/-30/0]_{2S}$ with about 0.005 in. ply thickness. These types of laminates were loaded to fracture in axial tension. The finite element model used in the simulation is shown in figure 4.

Progressive damage and fracture results obtained are summarized in figure 5 at several load levels indicated as a percentage of the fracture load. First damage indication appeared at 33 percent of the load. The damage continued to grow and extend until the load was increased to 100 percent of the fracture load. At this load CODSTRAN looped through several iterations. The first iteration, caused the extended damage shown in the first 100 percent schematic in figure 5. The last iteration destroyed all elements to the right of the cracks, indicating laminate global fracture with some bending as shown in the last schematic in figure 5.

CODSTRAN has also been used to study the damage growth and progressive fracture of laminates without defects, with center slits and with center holes (refs. 7 and 8). Progressive fracture results from this study are summarized in figure 6 at zero load and at fracture load, first iteration. As can be seen the progressive fracture is about the same for the laminates with the slit and with the hole. It is interesting to note that progressive fracture initiated at the center of the laminate without defects and advanced in generally similar directions as that in the laminates with the defects.

CODSTRAN keeps records of all the modes that initiate fracture at the macroscale (ply and interply) levels. A typical output of these records is summarized in Table I for the laminates shown in figure 6 and for different laminate configurations [$\pm\theta_s$]. These results provide considerable details with respect to weak modes in the laminate and with respect to its structural integrity and/or damage tolerance. In addition to records of fracture modes, CODSTRAN keeps records of plies destroyed, elements destroyed and nodes which do not connect elements. All this information is necessary to track the damage (defect growth and progressive fracture) at the various scales within which it occurs.

In order to assess the fracture toughness and service life of the laminate, CODSTRAN continued to track the crack or defect opening in either the local scale (between two adjacent nodes) or global (overall displacements) scale. Typical results for local crack opening displacement in laminates with center slits are shown in figure 7 for two laminate configurations. The results for the $[\pm 45]_s$ laminate show unbounded crack opening displacement for the same load and, therefore, imminent global (catastrophic) fracture once progressive fracture began. The results for the $[0]_4$ laminate showed several increases in load were required prior to imminent global (catastrophic) failure.

CONCLUSIONS

Progressive fracture in fiber composites can be computationally simulated using an integrated computer code such as CODSTRAN. The computational simulation tracks failure initiation, defect growth and damage, at the various scales in which these events occur. The computational simulation of progressive fracture provides extensive detailed information which can be used to detect failure initiation modes, damage growth (magnitude and direction), progressive fracture direction, and imminent global fracture. All this information makes it possible to computationally assess the structural integrity, damage tolerance and service life of fiber composite structures.

REFERENCES

1. Chamis, C.C.; and Smith, G.T.: CODSTRAN: Composite Durability Structural Analysis. NASA TM-79070, 1978.

2. McCormick, C.W., ed.: NASTRAN User's Manual (level 15). NASA SP-222(01), 1972.

3. Chamis, C.C.: Computer Code for the Analysis of Multilayered Fiber Composites - User's Manual. NASA TN D-7013, 1971.

4. Chamis, C.C.: Failure Criteria for Filamentary Composites. Composite Materials: Testing and Design, ASTM-STP-460, ASTM, 1969, pp. 336-351.

5. Sinclair, J.H.; and Chamis, C.C.: Fracture Surface Characteristics of Off-Axis Composites. NASA TM-73700, 1977.

6. Sinclair, J.H.; and Chamis, C.C.: Mechanical Behavior and Fracture Characteristics of Off-Axis Fiber Composites. I - Experimental Investigation. NASA TP-1081, 1977.

7. Irvine, T.B.; and Ginty, C.A.: Progressive Fracture of Fiber Composites. NASA TM-83701, 1983.

8. Ginty, C.A.; and Irvine, T.B.: Fracture Surface Characteristics of Notched Angleplied Graphite-Epoxy Composites. NASA TM-83786, 1984.

TABLE I. - FRACTURE MODE[a] OF $[\pm\theta]_s$ G/E LAMINATES
(PREDICTED BY CODSTRAN)

Notch type	Ply configuration: $[\pm\theta]_s$; θ in degrees									
	0	3	5	10	15	30	45	60	75	90
Unnotched solid	LT	LT S[3]	LT S[3]	LT S[3]	I S	S	I S	TT	TT	TT
Notched thru slit	LT S[1]	LT S	LT S	S	S	I S	I S	I TT S[2]	TT	TT
Notched thru hole	LT S	LT S	LT S	S	S LT	I S	I S TT	I TT	TT	TT

[a]LT = Longitudinal tension
TT = Transverse tension
S = Intraply shear:
1) Intraply shear occurring around notch tip during progressive fracture
2) Minimal intraply shearing during fracture
3) Some intraply shear occurring near constraints (grips)

I = Interply delamination

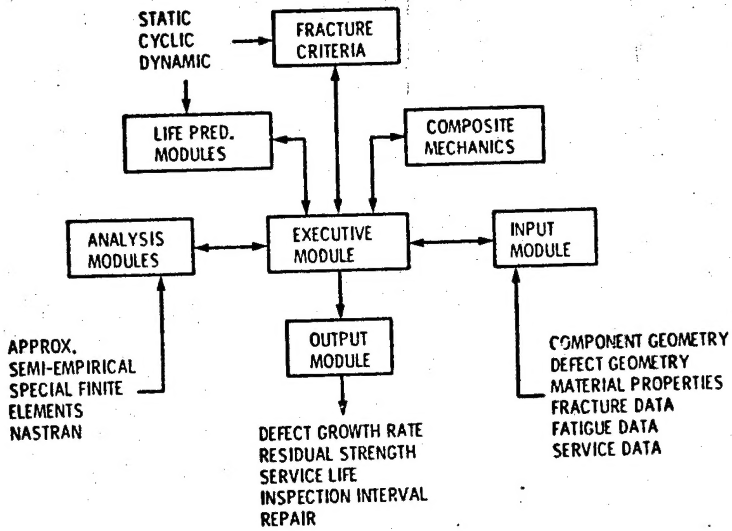


Figure 1. - CODSTRAN computer code schematic.

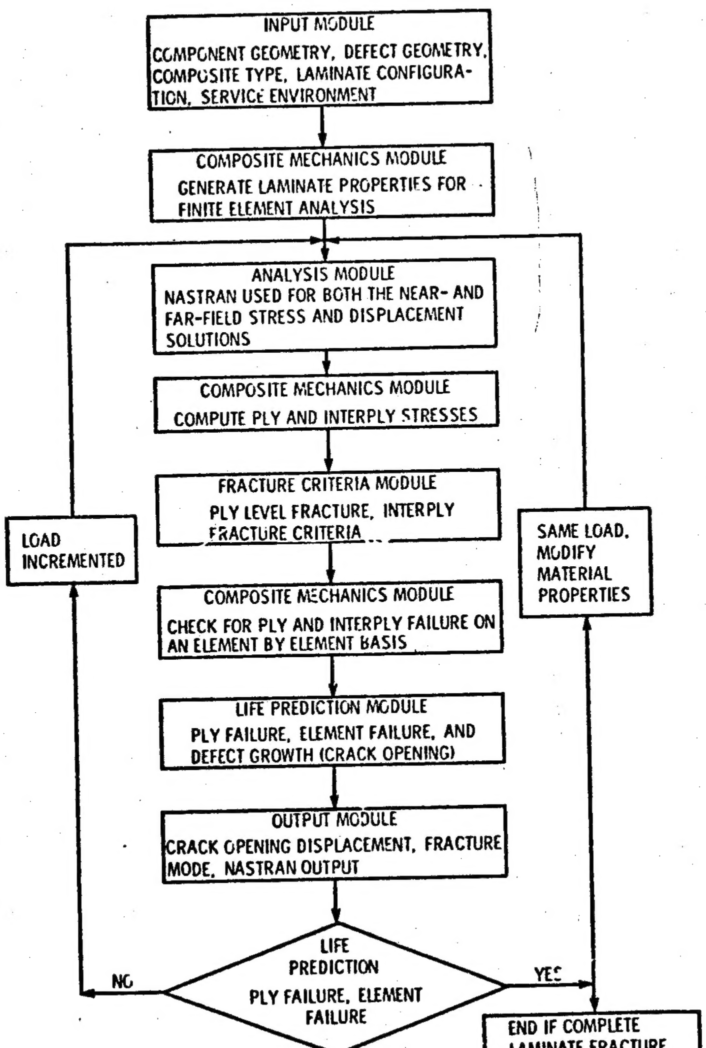


Figure 2. - CODSTRAN flow chart, computational simulation of progressive fracture.

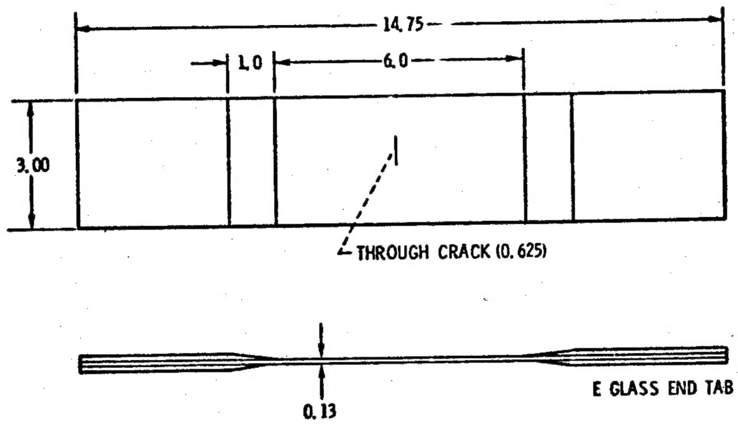


Figure 3. - Composite laminate test specimen geometry ($[0/30/0/-30/0]_{2S}$), Gr/E; dimensions in inches.

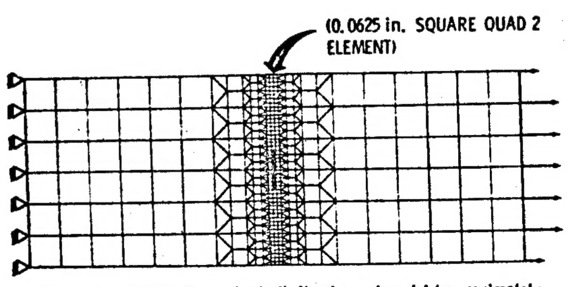


Figure 4. - Composite laminate finite element model (approximately 540 elements, 450 nodes, 870 DOF).

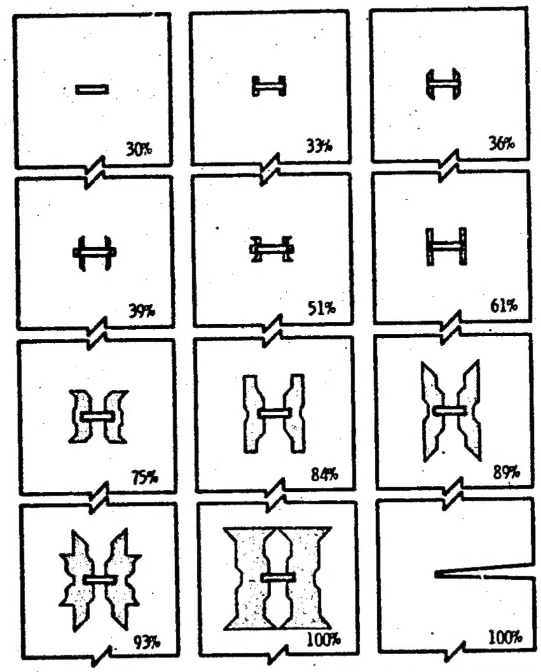


Figure 5. - Computationally simulated progressive fracture at various percentages of the fracture load (15 402 lb; Gr/E$[0/+30/0/-30/0]_{2s}$).

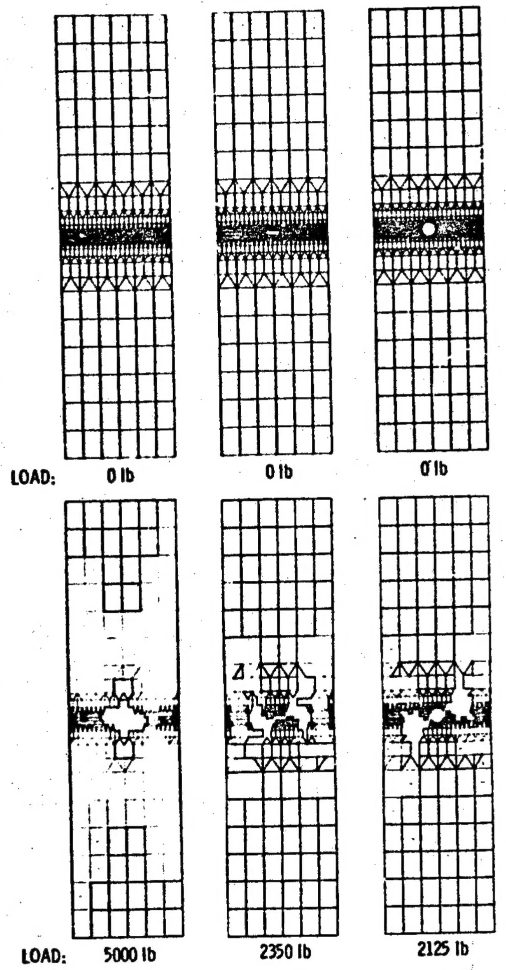


Figure 6. - Computationally simulated progressive fracture of laminates with different types of defects (Ge/E $[\pm 15]_s$).

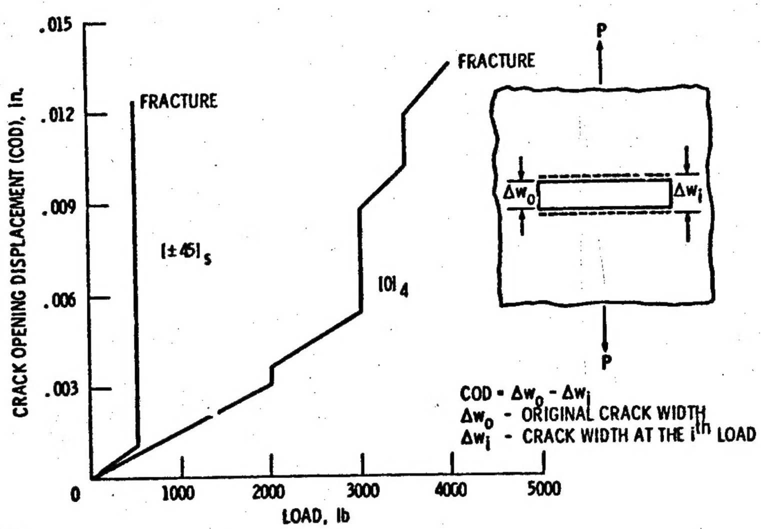


Figure 7. - Computationally simulated laminate behavior to fracture (Gr/E$[\pm\theta]_s$).

1. Report No. NASA TM-87341	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Computational Simulation of Progressive Fracture in Fiber Composites		5. Report Date
		6. Performing Organization Code 505-63-31
7. Author(s) Christos C. Chamis		8. Performing Organization Report No. E-3090
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the International Conference on Computational Mechanics sponsored by the International Committee on Computational Mechanics, Tokyo, Japan, May 25-28, 1986.

16. Abstract

Computational methods for simulating and predicting progressive fracture in fiber composite structures are presented. These methods are integrated into a computer code of modular form. The modules include composite mechanics, finite element analysis, and fracture criteria. The code is used to computationally simulate progressive fracture in composite laminates with and without defects. The simulation tracks the fracture progression in terms of modes initiating fracture, damage growth, and imminent global (catastrophic) laminate fracture.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Computer program; Failure modes; Composite mechanics; Failure initiation; Damage growth; Local fracture; Global fracture	Unclassified - unlimited STAR Category 24

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

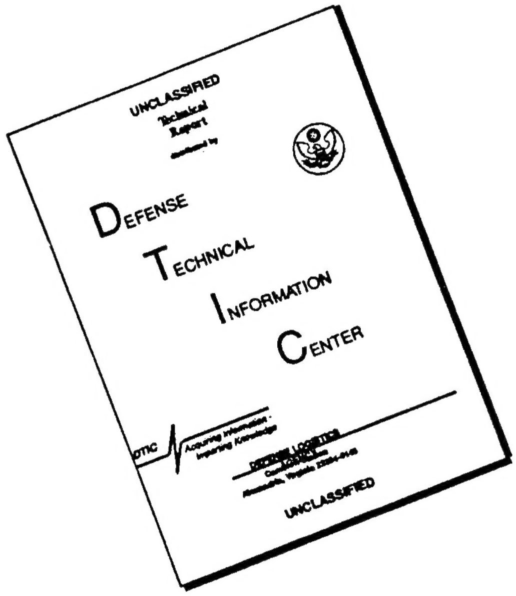
END

DATE

FILMED

AUG 13 1986

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.